



## DRAG REDUCTION WITH POLYMER MIXTURES IN OIL-WATER FLOWS: EFFECT OF SYNERGY

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**Abstract:** The pressure drop encountered during horizontal pipeline flows in chemical and petroleum industries require high pumping energy. It has been proven that frictional pressure drop in pipeline flows can be reduced by adding small amounts of high molecular weight polymeric solution. In this work, drag reduction (DR) in oil-water flows was investigated in 20 mm horizontal pipe diameter and length of 140 times the diameter (140\*D). Partially hydrolysed polyacrylamide (HPAM), polyethylene oxide (PEO) and aloe vera mucilage (AVM) as well as their mixtures (HPAM+AVM and PEO+AVM) at mixture Reynolds number of 37773 were used. Master solution of 2000 ppm and 20000 ppm for HPAM, PEO and AVM as well as their respective mixtures at total concentration (tc) of 30 ppm and 400 ppm were used. The two liquids used were tap water ( $\rho = 0.997 \text{ g/mL}$ ,  $\mu = 0.89 \text{ cP}$ ) and diesel oil ( $\rho = 0.832 \text{ g/mL}$ ,  $\mu = 1.66 \text{ cP}$ ) at ambient conditions (25 °C, 1 atm). Different oil input volume fractions ( $\beta_o$ ) and mixture velocities ( $U_{mix}$ ) for the two phases were used. Maximum DR of 61.67 & 63.33%, and 66.67 & 68.33% were obtained for HPAM+AVM and PEO+AVM respectively, at mixing ratios of 3:1 & 1:19, for 25% oil input and water-phase Reynolds number of 28329. These values (DR) obtained by polymer mixtures were higher than the DR obtained by individual polymer alone at the same conditions. An increase in  $\beta_o$  decreased DR due to decrease in the Reynolds number of the water phase. The rigidity and interaction between the polymer mixtures molecules may be responsible for the synergism in DR. The result showed that DR effectiveness can be improved by combining high molecular weight artificial and natural drag reducing polymers.

**Keywords:** Drag reduction, synergism, polymers, polymer mixture, Oil-water flow.

### INTRODUCTION

Transporting crude oil in pipeline systems is usually in mixture with water (1). High amount of pumping energy is required to overcome the pressure drop buildup in pipeline flow of these two immiscible fluids. The maintenance and installation of these pumps can lead to high operational cost in process industry. Hence, one of the key operations in oil and gas industry is the pipelines transportation of fluids (1-3).

Many researchers have proved that frictional pressure losses in pipeline flows can be reduced by adding small amount of higher molecular weight polymeric solution which is referred to as drag reduction (DR) (3-4). Thus, the pumping energy

requirement is reduced (5-6). DR has many industrial applications in different field which include drilling of oil from reservoir, crude oil pipeline transportation, filtration, irrigation and extraction among others (1, 7, 8). Recently, it was suggested for transportation of drinking water due to its harmless properties (9).

Drag reducing polymers (DRPs) are divided into artificial drag reducing polymer (HPAM, PEO, among others) and natural drag reducing polymer (guar gum, AVM, carboxymethyl cellulose among others). The efficiency of the natural drag reducing polymers is less than that of HPAM and PEO due to their rigidity but are more environmentally friendly (10-13). The incorporation of natural drag reducing polymer (AVM) onto HPAM and PEO can improve

the efficacy of DR and reduce environmental impact (12-13).

However, several oil-water flow (multiphase flow) patterns have been identified and classified by researchers. These include stratified flow, stratified flow with mixing at the interface, annular flow, dispersed flow, slug flow and plug flow among others (6-7). Multiphase flow patterns depend on density, viscosity, velocity, inclination and diameter, pipe roughness, surface wetting, and interfacial tension (14). Also, in multiphase flow  $Re$  is a function of density, viscosity, pipe diameter, superficial or mixture velocity, temperature, pressure and each phase volume fraction (14-15). The present research is limited to the use of polymer mixtures (HPAM+AVM and PEO+AVM) on pressure drop in pipeline multiphase flow (MPF). DR on oil-water flow have been carried out by many researchers (14-20).

Abubakar et al. (14) also studied DR with co-polymer (AN 105-SH) in horizontal oil-water flows in relatively large pipe diameter of 74.7 mm ID and length of 12 m. They reported that DR increased with increase in mixture velocity but decreased with increase in oil input volume fraction ( $\beta_0$ ). Edomwonyi-Otu and Angeli (1) explored on the effect of polymer addition on pressure drop and interfacial waves in horizontal oil-water flows using HPAM in 14 mm ID acrylic pipe with middle distillate as oily phase. They reported that mixture velocity affected the pressure drop in oil-water flows and small amount of DRP reduces drag for both single and multiphase flow. Al-Wahaibi et al. (16) studied effect of pipe diameter (19 mm and 25.4 mm) on DR in horizontal oil-water flows using magnafloc 1035 with concentration ranging from 2 - 30 ppm. DR of 60% in 25.4 mm and 45% in 19 mm ID pipe was achieved. Langsholt (17) used both water and oil soluble polymers at mixture velocity of 1.5 m/s. It was reported that DR in oil-water flows increased with increase in  $\beta_0$  of the drag reducing polymer soluble phase. Yusuf et al. (6) studied the effect of drag reducing polymer on pressure drop using Magnafloc 1035 with concentration ranging from 2 - 10 ppm in a horizontal pipe diameter of 25.4 mm ID and length of 8 m using high viscous oil (mineral oil). A maximum DR of 60% was achieved. Omer and Pal (18) also used two different molecular weight PEO and carboxymethyl cellulose with concentration ranging from 0 -1 wt% each, in different horizontal pipe ID. They observed a negative effect on pressure drop due to the insolubility of the drag reducing polymers in the oil phase. Al-Yaari et al. (19) used three different molecular weights of PEO of concentrations ranging from 10-15 ppm in 25.5 mm ID horizontal pipe and using kerosene as the oil phase. They reported that pressure drop is a function of water fraction, mixture velocity,

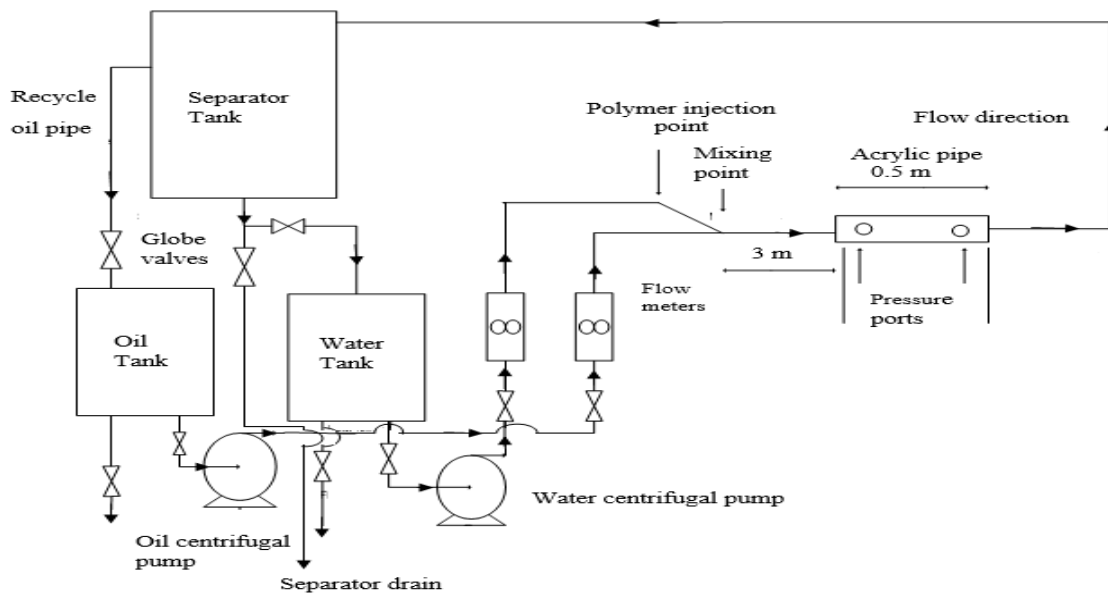
concentration and molecular weight of the drag reducing polymer and drag DR efficiency (DRE) decreases in the presences of salt water. Though, Al-Wahaibi et al. (20) was the first to report a documented work on DR in oil-water flows. They investigated the effect of two concentrations (20 & 50 ppm) of Magnafloc 1011 in 14 mm ID horizontal acrylic pipe on oil-water flows. They achieved the maximum DR of 50%. They also observed that pressure drop decreases with increased in the water phase velocity which is similar with the findings of Al-Yaari et al. (19).

Despite the works done in understanding the mechanism of DR in oil-water flow using polymer mixtures, the literature is rather insufficient. There is also the need to develop robust models for the accurate prediction of DR in synergistic system and these require a lot of data than is currently available. Thus, the main focus of this work is to study the effect of the combine polymer mixtures (HPAM+AVM and PEO+AVM) in horizontal oil-water flows.

## METHODS

### Description of the flow facility

The diagrammatic representation of the flow facility is shown in Figure 1. It is divided into three main parts: the handling section, pumping or regulating section and the flow measuring section. The handling section consists of three tanks where the fluids are stored: the oil, and water tanks are each 200 litres while the separator is 220 litres in capacity. Gravity is the main principle of separation in the separator where water is drained through the bottom opening while the separated oil is recycled. The 20 mm ID unplasticised polyvinylchloride (uPVC) pipes are each connected to water and oil tanks and m. The centrifugal pumps (model Jet 102M/N.31227) with maximum flow rate of 65 L/min each were used to circulate the test fluids into the test section. The flow rates which were measured with variable area flow meters (LZM-20J;  $\pm 3\%$  accuracy) are controlled by gate valves and are separated for each fluid. The meter for the water line flows at  $\leq 24$  GPM or 100 LPM and it was calibrated before the experiments begin. The injection port for the polymer master solution is located by the side of the water pipeline before the Y-junction. The programmable peristaltic injection pump (model NE-9000;  $\pm 1\%$  accuracy) was used to add the master solution in the water line. The internal diameter of the acrylic pipe is 20 mm ID with a length greater than  $140 \times D$  from the mixing point (Y-junction) to the next pressure measuring point, which are 1.5 mm in size at lower portion of the pipe walls. They were at a location that ensures that fully developed flow in the test section is attained before measurements.



**Figure 1:** Schematics of experimental flow rig.

### Polymer preparation

The polymers used are partially hydrolysed polyacrylamide, HPAM (Magnafloc 1011) manufacture by BASF chemicals  $10 \times 10^6$  g/mol, polyethylene oxide (PEO) manufacture by Sigma-Aldrich with average molecular weight of  $8 \times 10^6$  g/mol, and Aloe Vera mucilage (AVM) extracted from Aloe Vera plant. All the polymers are water soluble and were used without further purification. The individual solutions of the polymers were prepared firstly, before the solution of polymer mixture. A master solution of 2000 ppm of each of the synthetic polymer was prepared as follows. 10 g of each of the polymeric powder was measured using weighing balance (Kerro, BLC 3002) and gently spread over 5 litres of surface of water and stirred for 3 hours with a mechanical stirrer (Gilverson, L28) at a very low speed (to avoid degradation of the polymer) for the mixture to be completely homogenised. The stirred solution was left for 12 hours, mostly overnight, to ensure complete dissolution of the polymeric particles and removal of trapped gas bubbles to form the master solution (21, 7). Aloe Vera leaves were harvested from a garden then washed thoroughly. The leaves were then cut vertically on both sides and soaked in water for 10 minutes, to remove the Aloin within them. The leaves were then peeled and the Aloe Vera mucilage (AVM) was extracted by scraping and sieving the gel from the leaves (22). Aloe Vera leaf contains about 98% water while the remaining 2 % is the AVM (23-24). 20,000 ppm master solution of AVM was prepared. AVM suffers biological degradation in 24 hours. After the preliminary experiments with each of the polymer solutions in single phase water flow, the total concentration ( $t_c$ ) for any mixture was chosen based on the fact that at least one of the polymers in the mixture gave maximum DR at that concentration (25). In case of this work, 30 ppm

and 400 ppm were selected as the total concentration for the mixture of HPAM-AVM and PEO-AVM. The mixtures master solution of 2000 ppm and 20,000 ppm were prepared at different mixing ratio to achieve the required concentration of the polymer mixtures in the flow line as described by Reddy & Singh and Malhotra et al. (26, 25). 200 millilitres of 20,000 ppm of AVM master solution was measured and diluted with 8000 millilitres of water to achieved 500 ppm. 1500 ppm of the synthetic polymers (HPAM & PEO) was mixed with 500 ppm of AVM and stirred for 3 hours and the stirred solution was left for 12 hours to form a master solution of 2000 ppm for the polymer mixtures. It was injected into the aqueous phase at specific flow rate in order to achieved the require concentration in the water flow line.

### Procedure

The injection pump and flow metres were tested before running the experiments to ensure accurate delivery of the required amounts of oil and water into the test section, and the polymeric master solution into the water phase. The experiment was carried out in horizontal pipe diameter of 20 mm ID and length of  $140 \times D$  at ambient conditions ( $25^\circ\text{C}$ , 1 atm). The U-tube manometer was used to for the pressure drop measurement. The experiments were performed at least three times with a standard deviation less than 2.5%. HPAM, PEO, AVM, HPAM+AVM and PEO+AVM were tested at different concentrations and Reynolds numbers. The concentrations of HPAM and PEO ranging from 2.5 - 100 ppm while the concentration of Aloe Vera mucilage (AVM) ranging from 5 - 500 ppm at flow rates of 10 L/min, 20 L/min, 30 L/min and 40 L/min ( $Re$  from 12916 - 48871). The optimal polymer concentration of 30 ppm (for HPAM & PEO) and 400 ppm (for AVM) were obtained from preliminary experiments of a single-phase water flow. The

optimal concentrations were selected to be the total concentration ( $t_c$ ) for the polymer mixture (25). The preliminary experiment of the polymer mixtures (HPAM+AVM & PEO+AVM) was conducted at different mixing ratio for the  $t_c$  of 30 ppm and 400 ppm at different Re (12916 - 48871). The mixing ratio of 3:1 and 1:19 was chosen due the fact that, maximum DR was achieved at that mixing proportion from the preliminary experiment conducted. HPAM, PEO, AVM, HPAM+AVM and PEO+AVM were tested at different oil input volume fraction ( $\beta_o$ ) and mixture Reynolds number (Mix-Re; mixture velocity,  $U_{mix}$ ). The Mix-Re was obtained from the summation of the water phase Reynolds number and that of the oil phase, at different superficial velocities of water ( $U_{sw}$ ) and oil ( $U_{so}$ ). The concentrations of 30 ppm (HPAM & PEO) and 400 ppm (AVM) were tested at Reynolds number of 37773. The various proportion of the oil input volume fractions were 0, 25, 50, 75 and 100%.

The pressure drop was recorded and used for calculation of DR; defined by the given Equation 1 below:

$$DR = \frac{\Delta P_w - \Delta P_\phi}{\Delta P_w} \times 100\%$$

Where;  $\Delta P_w$  and  $\Delta P_\phi$  is pressure drop of the fluid with and without DRPs.

## RESULTS AND DISCUSSION

Only the mean values of the pressure drop obtained from three measurements were used in the calculation of percentage drag reduction (DR). The DR calculated using Equation 1 was presented graphically in two ways; at first DR against  $\beta_o$  at different Mix-Re and second against Mix-Re at different  $\beta_o$ .

### DR in Single Phase Water Flow

The DR of HPAM, PEO, AVM, HPAM+AVM & PEO+AVM was studied in single phase water flow at

different concentrations and Reynolds number. The maximum DR of 50%, 70% & 72%, for AVM, HPAM & PEO; 75.2% & 82.5% for HPAM+AVM (3:1 & 1:19) and 78% & 83% for PEO+AVM (3:1 & 1:19) respectively were obtained. The optimal concentration of 30 ppm (HPAM & PEO), 400 ppm (AVM), 22.5 ppm - 7.5 ppm (HPAM+AVM & PEO+AVM at  $t_c$  of 30 ppm), and 20 ppm - 380 ppm (HPAM+AVM & PEO+AVM at  $t_c$  of 400 ppm) were achieved at Reynolds number of 37773 in the preliminary experiments. The results obtained are in agreement with the work of Reddy & Singh (25) and Malhotra et al. (26).

### DR by Polymers in Multiphase flow

The DR of HPAM, PEO and AVM was studied in MPF at different  $\beta_o$  and Mix-Re. Figures 2 - 4 show the results of the effect of  $\beta_o$  and Mix-Re on DR in oil-water flows for HPAM, PEO and AVM. It was observed that DR declined with increase in  $\beta_o$  due to decrease in the Reynolds number of the water dominated region because the drag reducing polymers (HPAM, PEO and AVM) used were only soluble in the water phase. This agree with the findings of Yusuf et al. (6) and Edomwonyi-Otu et al. (7).

Moreover, At 75 -100%  $\beta_o$ , high pressure drop was observed owing to the fact that the larger portion of the pipe was occupied by the oily phase, which reduces the Reynolds number of the water phase, as such reduced the DR. It was also observed that increased in Mix-Re increases  $U_{sw}$ , which creates high degree of turbulence in the water phase thus cause better interaction between the DRPs and turbulent eddies. At high turbulence in the water phase DRPs suppress the formation and propagation of this eddies which reduce the pressure drop as well the pumping energy in oil-water flow. This corroborate with the previous findings of (6-7, 14-16, 20-21).

DR of 61.67%, 58.33% and 43.33% for PEO, HPAM and AVM respectively were achieved at 25%  $\beta_o$  and water phase Reynolds number of 28329.

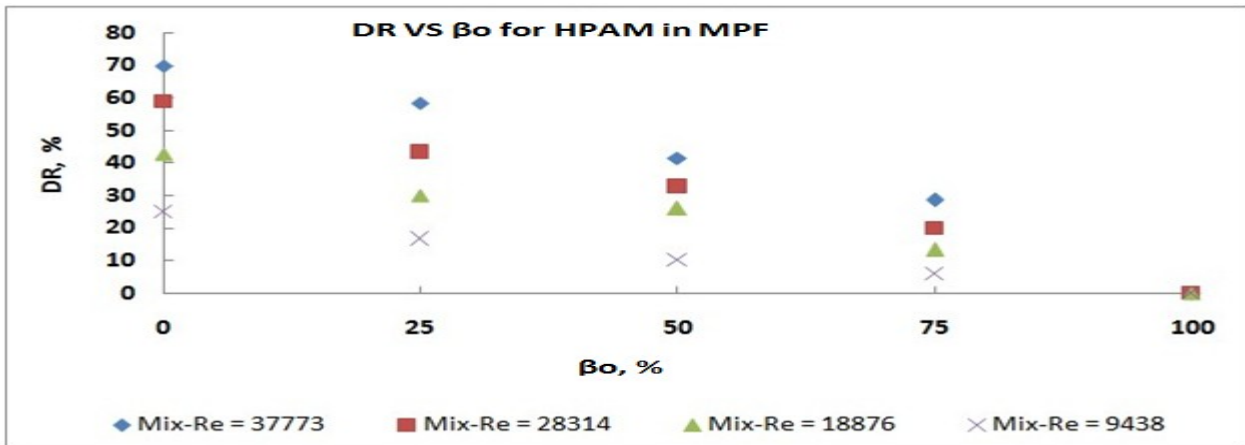


Figure 2: DR vs  $\beta_0$  for HPAM at different Mix-Re at concentration of 30 ppm in 20 mm pipe diameter.

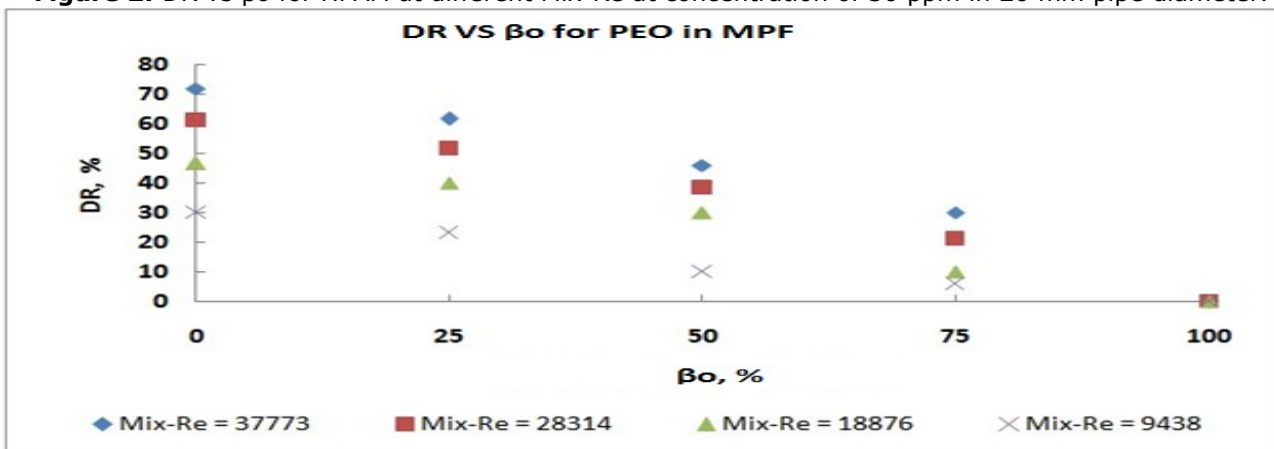


Figure 3: DR vs  $\beta_0$  for PEO at different Mix-Re at concentration of 30 ppm in 20 mm pipe diameter.

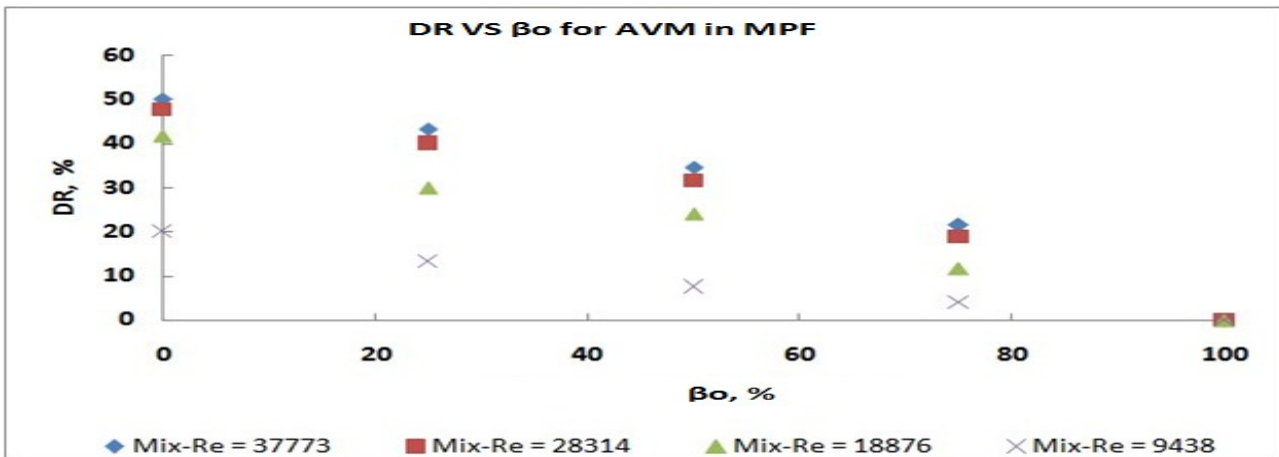


Figure 4: DR vs  $\beta_0$  for AVM at different Mix-Re at concentration of 30 ppm in 20 mm pipe diameter.

#### DR Polymer Mixtures in Multiphase Flow

The DR of HPAM+AVM and PEO+AVM was studied in oil-water flows at different  $\beta_0$  and Mix-Re. The total concentration ( $t_c$ ) of 30 ppm and 400 ppm at mixing ratio of 3:1 and 1:19 for the master solution of 2000 ppm and 20,000 ppm were used for the polymer mixtures. Figures 5 - 8 show the results of the effect of  $\beta_0$  and Mix-Re on DR in oil-water flows for a mixture of HPAM+AVM and PEO+AVM. Similar

declination in DR observed resulted from decrease in water phase Reynolds number due to decrease in Mix-Re (27-28). It was also observed that at the same conditions DR obtained by the polymer mixtures (61.67% & 66.67% for HPAM+AVM at 3:1 & 1:19; 63.33% & 68.33% for PEO+AVM at 3:1 & 1:19) was higher than the DR of each polymer present in the polymer mixture. The synergy in DR in the oil-water flow by polymer mixtures may be

due to the presence of other polymer molecules which improve the rigidity (flexibility) of the DRPs (27-28)(29, 25).

used, this is in agreement with the previous works (29, 25).

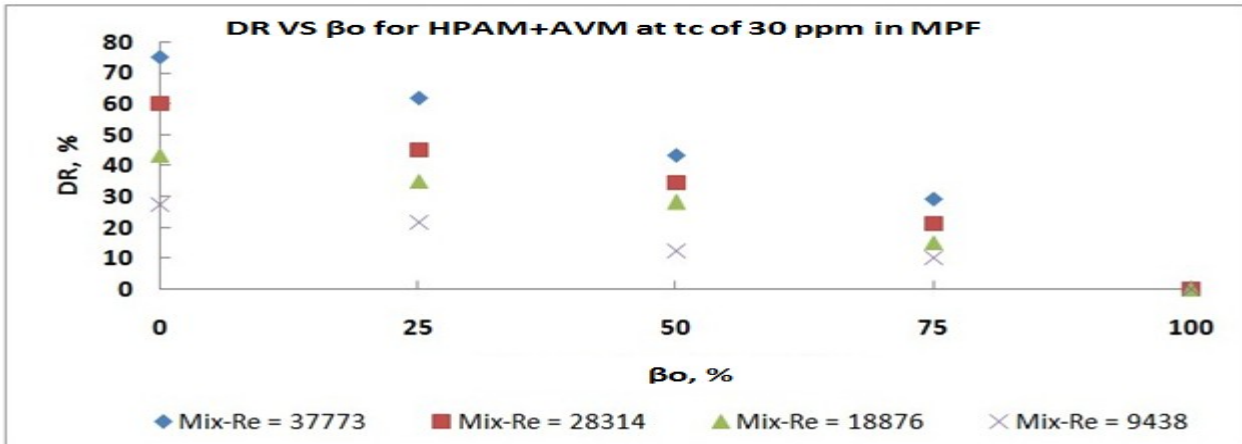


Figure 5: DR vs  $\beta_0$  for HPAM+AVM mixture ratio of 3:1 at different Mix-Re and  $t_c$  of 30 ppm in 20 mm pipe diameter.

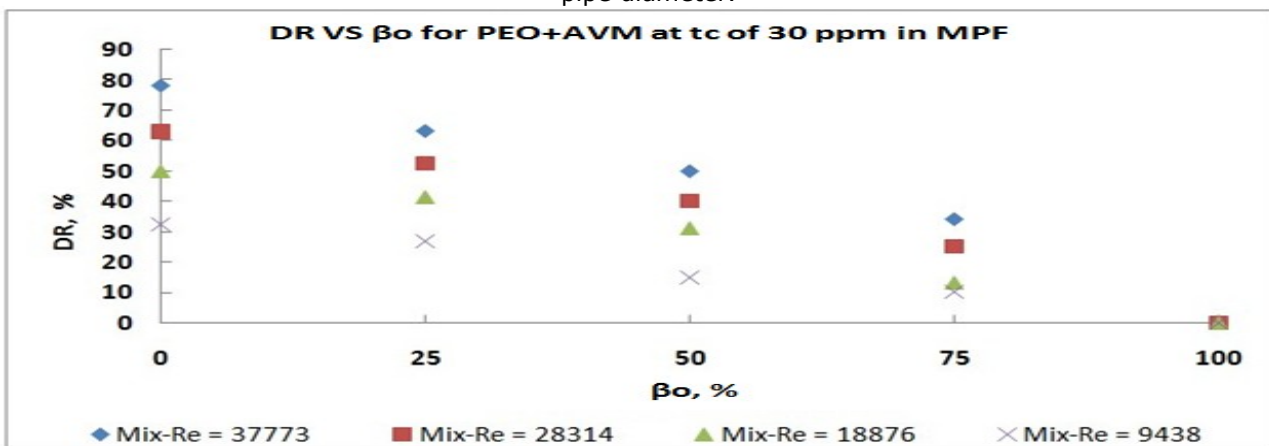


Figure 6: DR vs  $\beta_0$  for PEO+AVM mixture ratio of 3:1 at different Mix-Re and  $t_c$  of 30 ppm in 20 mm pipe diameter.

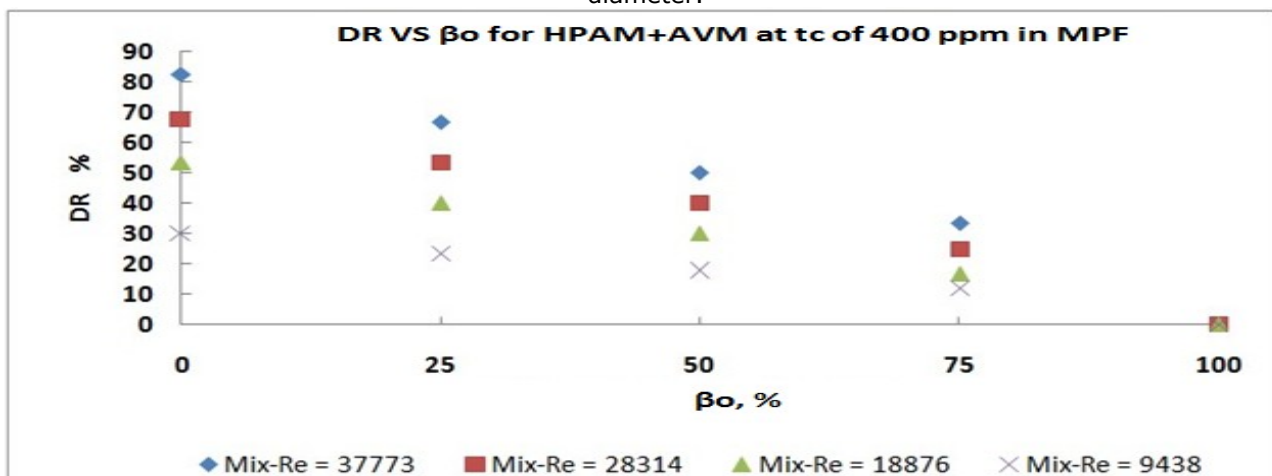
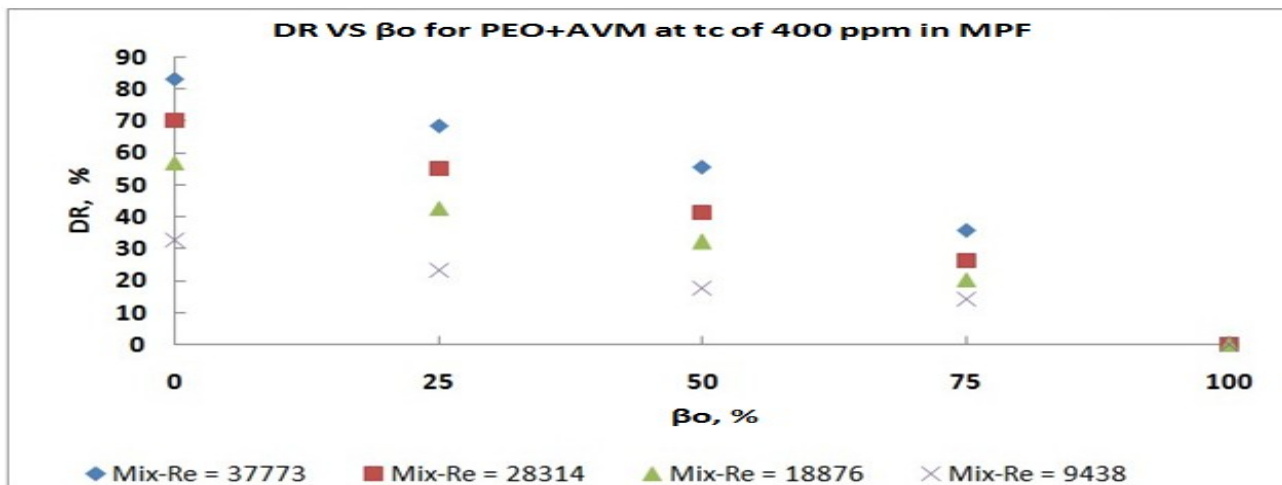


Figure 7: DR vs  $\beta_0$  for HPAM+AVM mixture ratio of 1:19 at different Mix-Re and  $t_c$  of 400 ppm in 20 mm pipe diameter.



**Figure 8:** DR vs  $\beta_o$  for PEO+AVM mixture ratio of 1:19 at different Mix-Re and tc of 400 ppm in 20 mm pipe diameter.

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